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HD 80606 b, a planet on an extremely elongated orbit*

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Abstract. We report the detection of a planetary companion orbiting the solar-type star HD 80606, the brighter component of a wide binary with a projected separation of about 2000 AU. Using high-signal spectroscopic observations of the two components of the visual binary, we show that they are nearly identical. The planet has an orbital period of 111.8 days and a minimum mass of 3.9 $M_{\rm Jup}$. With $e = 0.927$, this planet has the highest orbital eccentricity among the extrasolar planets detected so far. We finally list several processes this extreme eccentricity could result from.

Key words. techniques: radial velocities – stars: individuals: HD 80606 – stars: individuals: HD 80607 – binaries: visual – extrasolar planets

1. Introduction

We report in this paper on our radial-velocity measurements of HD 80606, the primary star of the visual binary system HD 80606–HD 80607. These observations reveal the presence of a 3.9 Jovian-mass planet (minimum mass) in a very eccentric orbit around this solar-type star.

The variable velocity of HD 80606 was first noticed by the *G–Dwarf Planet Search* (Latham 2000), a reconnaissance of nearly 1000 nearby G dwarfs that uses the HIRES high-resolution spectrograph (Vogt et al. 1994) mounted on the 10-m Keck 1 telescope at the W. M. Keck Observatory (Hawaii, USA) to identify extrasolar planet candidates. The star was then followed up by the *ELODIE Planet Search Survey team* (Mayor & Queloz 1996; Udry et al. 2000) using the ELODIE fiber-fed echelle spectrograph (Baranne et al. 1996) mounted on the Cassegrain focus of the 1.93–m telescope at the Observatoire de Haute-Provence (CNRS, France).

The ELODIE velocities are obtained by cross-correlating the observed spectra with a numerical template. The instrumental drifts are monitored and corrected using the "simultaneous thorium-argon technique" with dual fibers (Baranne et al. 1996). The achieved precision with this instrument is of the order of 10 m s^{-1}. The HIRES instrumental profile and drifts are monitored using an iodine gas absorption cell (Marcy & Butler 1992). The radial velocities are derived from the spectra using the TODCOR code (Zucker & Mazeh 1994), a two-dimensional correlation algorithm.

The observations of HD 80606 started in April 1999 with HIRES. With a velocity difference of 267 m s^{-1} in less than one month between the first two measurements, the variability of this source was quickly detected. In July 1999, we started an ELODIE radial-velocity follow up of 6 non-active slow-rotating radial-velocity variable stars detected with HIRES, including HD 80606. The first ELODIE measurement for this star was obtained during our November 1999 run. The discovery of the planetary companion orbiting HD 80606 has been recently announced together with 10 other new extrasolar planet candidates (April 4th 2001 ESO PR[1]). Among these is the planetary companion to HD 178911 B

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[1] www.eso.org/outreach/press-rel/pr-2001/pr-07-01.html

(Zucker et al., in prep.), another one of the candidates identified with HIRES.

The stellar characteristics of the two components of the HD 80606–HD 80607 visual binary are presented in Sect. 2. The radial-velocity data and the orbital solution are presented in Sect. 3. The very high orbital eccentricity is discussed in Sect. 4. The 61 radial-velocity measurements presented in Sect. 3 as well as the iron line list we used in Sect. 2 will be made available in electronic form at the CDS in Strasbourg via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/375/L27`

2. Stellar properties

HD 80606 (HIP 45982) and HD 80607 (HIP 45983) are the two components of a visual binary system. They have common proper motions and the fitted systemic velocity for HD 80606 ($\gamma = 3.767 \pm 0.010\,\mathrm{km\,s^{-1}}$) is almost equal to the mean radial velocity measured for HD 80607 ($\langle RV \rangle = 3.438 \pm 0.025\,\mathrm{km\,s^{-1}}$). The difference between the two values can be explained by the binary orbital motion. The main stellar characteristics of HD 80606 and HD 80607 are listed in Table 1. The spectral types, apparent magnitudes, colour indexes, parallaxes and proper motions are from the HIPPARCOS Catalogue (ESA 1997). The projected stellar rotational velocity, $v \sin i$, was measured using the mean ELODIE cross-correlation dip width and the calibration by Queloz et al. (1998). The rms of the HIPPARCOS photometric data is large for both stars ($\sigma_{H_\mathrm{p}} \simeq 40$ mmag) but this measured scatter is classified as *"duplicity–induced–variability"* in this catalogue. The angular separation between the two visual components is about $30''$. This value is not much larger than the satellite detector size so contamination from one component onto the other is probably responsible for the observed scatter. The contamination is also probably responsible for the difference in parallaxes (a factor of two) and for the abnormally large uncertainties on this parameter ($\sigma_\pi \simeq 1$ mas is expected with HIPPARCOS for a 9th magnitude star).

We derived the atmospheric parameters (LTE analysis) using HIRES high signal–to–noise spectra with the same method as in Santos et al. (2000a). We used the same line list and oscillator strengths as these authors, except for some lines that could not be used because they were out of the HIRES spectral coverage or fell just between two non-overlapping orders of the echelle spectra. Our line list finally consisted of 18 Fe I lines and only 3 Fe II lines. We estimated the uncertainties on the derived atmospheric parameters in the same way as in Gonzalez & Vanture (1998). The two stars have almost the same iron abundance and are very metal-rich dwarfs (respectively 2.7 and 2.4 times the solar iron abundance). An independent study (Buchhave et al., in prep.) using the same HIRES spectra but a different line list gives consistent results. For the lithium abundance measurement, we summed all our ELODIE spectra in the λ 6707.8 Å Li I line region. No trace of lithium was detected giving upper limits (3–σ confidence level) on the corresponding equivalent widths for both stars. The abundance upper limits were then derived using the curves of growth by Soderblom et al. (1993). The lithium abundances are scaled with log(H) = 12.

Table 1. Observed and inferred stellar parameters for HD 80606 and HD 80607.

		HD 80606	HD 80607
Sp. Type		G5	G5
m_V		9.06 ± 0.04	9.17 ± 0.04
$B-V$		0.765 ± 0.025	0.828 ± 0.029
π	(mas)	17.13 ± 5.77	9.51 ± 8.76
Distance	(pc)	58.4 $\pm^{29.6}_{14.7}$	105 $\pm^{1228}_{51}$
$\mu_\alpha \cos(\delta)$	(mas yr^{-1})	46.98 ± 6.32	42.90 ± 9.23
μ_δ	(mas yr^{-1})	6.92 ± 3.99	8.26 ± 5.88
T_eff	(K)	5645 ± 45	5555 ± 45
$\log g$	(cgs)	4.50 ± 0.20	4.52 ± 0.15
ξ_t	(km s^{-1})	0.81 ± 0.12	0.91 ± 0.12
[Fe/H]		0.43 ± 0.06	0.38 ± 0.06
$v \sin i$	(km s^{-1})	0.9 ± 0.6	1.4 ± 0.4
$W_{\lambda,\mathrm{Li}}$	(mÅ)	<2.5	<3.0
$\log n$(Li)		<0.78	<0.77

3. Radial-velocity analysis and orbital solution

On the 24th of April 2001, we had in hand a total of 61 radial-velocity measurements for analysis: 6 from HIRES and 55 from ELODIE. The mean uncertainty on the velocities are of the order of 14 m s^{-1} (systematic error + photon noise) for both instruments. The HIRES velocities have an arbitrary zero point. From contemporaneous observations, we applied a preliminary shift to these velocitites to bring them to the ELODIE system: $\Delta RV = +3.807\,\mathrm{km\,s^{-1}}$. To account for possible errors in this zero-order shift, the orbital solution presented in Table 2 includes the residual velocity offset $\Delta RV_\mathrm{H-E}$ between HIRES and ELODIE as an additional free parameter. The obtained $\Delta RV_\mathrm{H-E}$ is consistent with zero. Figure 1a shows the temporal velocities for HD 80606. The phase-folded velocities are displayed in Fig 1c. The fitted orbital eccentricity is extremely high – $e = 0.927 \pm 0.012$. Assuming a mass of 1.1 $M_\odot$ for HD 80606, a typical value for a very metal-rich star with a solar effective temperature, the planetary companion minimum mass is $m_2 = 3.90 \pm 0.09$ M_Jup. The semimajor axis is 0.469 AU and the orbital separation ranges from 0.034 AU (periastron) to 0.905 AU (apastron).

The residuals to the fitted orbit cannot be explained by our measurement errors. The computed χ^2 probability for the full set of data is lower than 10^{-3} ($\chi^2 = 102.45$, $\nu =$ number of degrees of freedom $= N - 7$ free parameters $= 54$). Our measurement errors are correctly estimated for both instruments (see e.g. the low residuals value obtained for HD 178911 B, Zucker et al., in prep.). The very low $P(\chi^2)$ value found for HD 80606 can therefore not result from an underestimation of our measurement errors. Using our HIRES high-signal spectrum, no chromospheric emission is detected for HD 80606 so the expected stellar jitter is low (a few m s^{-1}, see e.g. Santos et al. 2000b; Saar et al. 1998). Activity related processes

Table 2. Fitted orbital elements to the radial-velocity measurements for HD 80606. The velocities obtained with the HIRES spectrograph (H) have been set into the ELODIE (E) system.

P	days	111.81	$\pm$ 0.23
T	HJD	2 451 973.72	$\pm$ 0.29
e		0.927	$\pm$ 0.012
γ	km s^{-1}	3.767	$\pm$ 0.010
w	$^\circ$	291.0	$\pm$ 6.7
K_1	m s^{-1}	411	$\pm$ 31
$\Delta RV_{\rm H-E}$	m s^{-1}	1.5	$\pm$ 8.5
$a_1 \sin i$	10^{-3} AU	1.581	$\pm$ 0.037
$f_1(m)$	10^{-8} $M_\odot$	4.26	$\pm$ 0.29
$m_2 \sin i$	$M_{\rm Jup}$	3.90	$\pm$ 0.09
N		55(E) + 6(H)	
$\sigma_{\rm O-C}$	m s^{-1}	17.7 (E:16.3, H:29.9)	

are therefore probably not responsible for the observed residuals. The later could be explained by the presence of another planet around HD 80606 on a longer period orbit perturbating the stellar radial-velocity signal induced by the inner companion. No clear velocity trend was detected from the residuals curve (see Fig. 1b). Future measurements should help to solve the question.

4. Discussion

The fitted orbital eccentricity is the highest found so far for an extrasolar planet orbiting a solar-type star. The orbital eccentricities for extrasolar planets with period longer than 100 days almost cover the full possible range (Mayor & Udry 2000; Udry & Mayor 2001): from nearly circular (see e.g. the recently announced planet around HD 28185, $P = 385$ days, $e = 0.06$, ESO PR[2]) to nearly unity, as in the case of HD 80606. The distribution of the eccentricities of the planetary orbits might be a keystone in understanding the formation processes of planets, as was pointed out early in the study of extrasolar planets by Mazeh et al. (1997b).

Before discussing any mechanism that could have generated the eccentricity of HD 80606, it is interesting to note that the eccentricity distribution of the planets with long orbital periods found so far is strikingly similar to that of the binary orbits (Heacox 1999; Stepinski & Black 2000, 2001; Mayor & Udry 2000; Mazeh & Zucker 2000). In particular, the high eccentricity of HD 80606 is very similar to one of the highest eccentricity found so far for a spectroscopic binary – 0.975 (Duquennoy et al. 1992). The similarity of the two eccentricity distributions does not prove that the planets and the low-mass stellar companions come from the same population. The large gap between the mass distribution of the planets and that of the stellar companions (Jorissen et al. 2001; Zucker & Mazeh 2001) and the differences in the metallicity distributions for stars with and without planets (Santos et al.

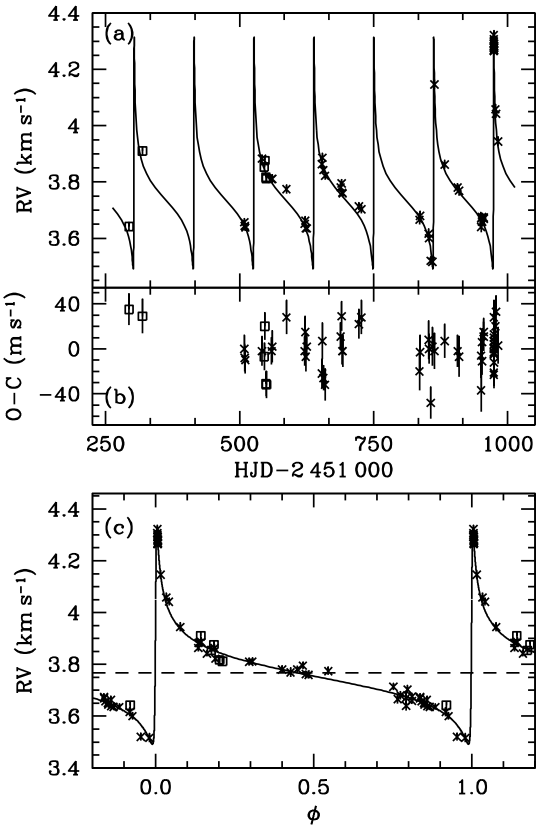

Fig. 1. HD 80606 radial-velocity data. Crosses: Elodie-OHP measurements. Open squares: Hires-KECK measurements. **a)** Temporal velocities. **b)** Residuals around the solution. **c)** Phase-folded velocities.

2001) strongly suggests that we are dealing with two distinct populations. Nevertheless, we might need to look for mechanism(s) that can produce a range of eccentricities from zero up to unity for the two populations.

A mechanism to generate eccentric orbits could be the gravitational interaction of a planet (and a binary) with a disk (Artymowicz et al. 1991; Artymowicz 1992). However, a recent study (Papaloizou et al. 2001) suggests that for a standard disk model this can happen only for massive companions, at least in the range of brown dwarf masses. For companions with planetary masses the disk probably acts to damp the eccentricity growth, and therefore can not explain the observed high eccentricities.

Another possible mechanism is the gravitational interaction with another planet(s). This could be via dynamical instability (e.g. Weidenschilling & Marzari 1996; Rasio & Ford 1996; Lin & Ida 1997; Ford et al. 2001) or through some resonant interaction with a disk and another planet (Murray et al. 2001). The instabilities naturally lead to high eccentricities, specially if they involve ejection of another planet out of the system. The resonant interaction, on the other hand, seems to need some fine tuning for generating eccentricities as high as the one found here.

A possible clue to the origin of the particularly high eccentricity found here could have been found in the fact that HD 80606 resides in a stellar wide binary. At least one

[2] www.eso.org/outreach/press-rel/pr-2001/pr-07-01.html

other planet, the one orbiting 16 Cyg B, was found with a high eccentricity in a wide binary. A few studies (Mazeh et al. 1997a; Holman et al. 1997) have suggested that the high eccentricity of 16 Cyg B is because of the gravitational interaction with the distant stellar companion. In this model, the *"tidal"* interaction of the distant companion induces an eccentricity modulation into the planetary orbit on a long timescale. The present phase of the cycle is close to the highest point of the eccentricity modulation.

However, this interpretation does not apply here. This is so because the modulation timescale induced by HD 80607 is of the order of 1 Gyr (e.g. Mazeh & Shaham 1979). This is very long relative to the relativistic periastron passage modulation, which is of the order of 1 Myr. The precession of the longitude of the periastron induced by the relativistic effect completely suppresses the third-body modulation. To hold on to the third-body interpretation we have to *assume* an additional body in the system, in an orbit around HD 80606 with a period of the order of 100 yrs. The present radial-velocity measurements can not rule out such a companion. To be consistent, this model has to apply for all the planets with high eccentricity, above, say, 0.6 – an eccentricity that does not seem to be that rare anymore. Note also that this model requires a large angle between the plane of motion of the planet and that of the perturbating body.

In short, as stressed by Mayor et al. (2000) and Stepinski & Black (2001), we need a consistent model that will account for the distribution of eccentricities of the planetary orbits and for its similarity to the distribution for stellar companions. It seems that further observations and theoretical work are needed to reach a consensus about such a model.

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